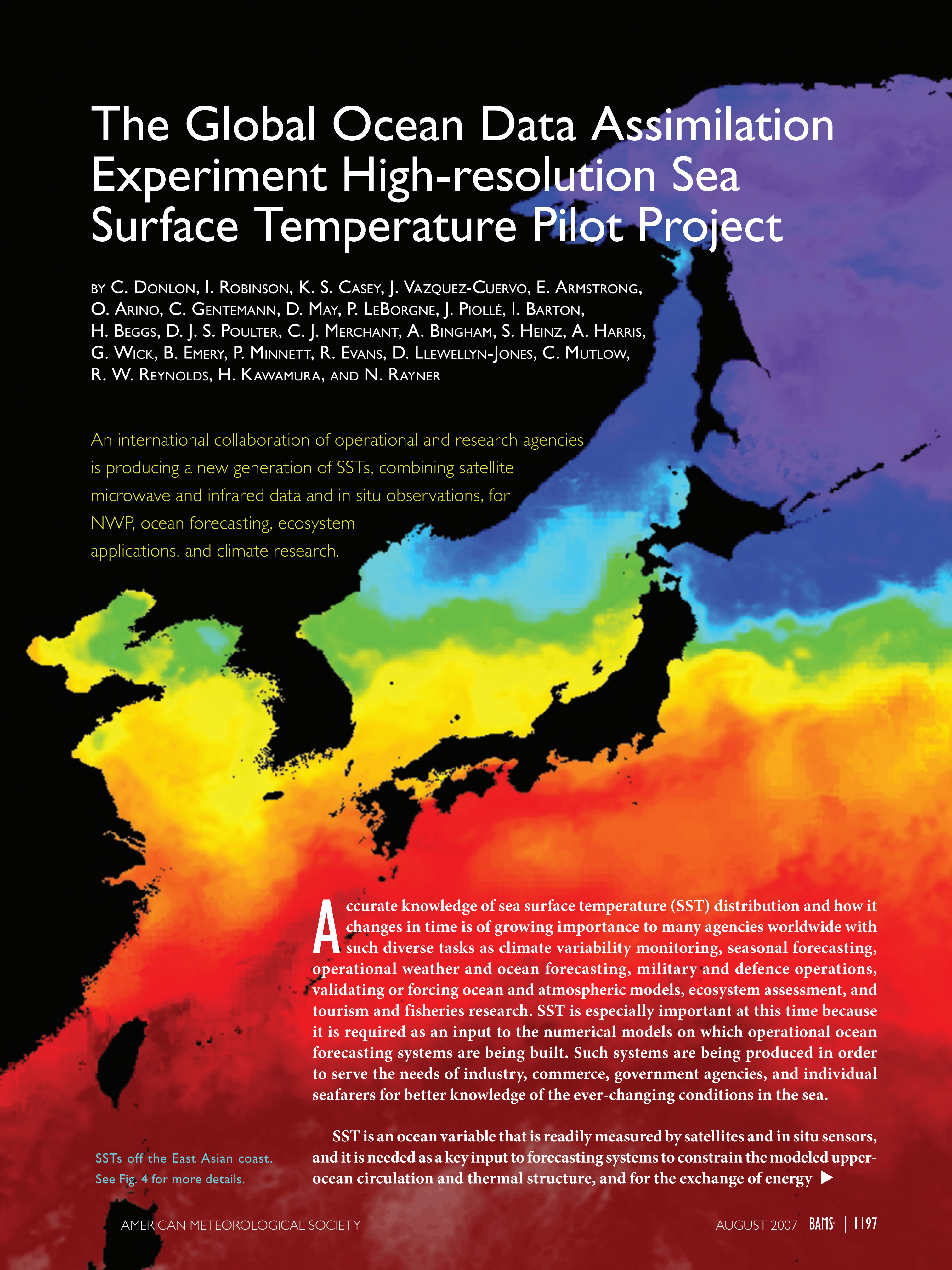
The Global Ocean Data Assimilation Experiment High-resolution Sea Surface Temperature Pilot Project

BY C. DONLON, I. ROBINSON, K. S. CASEY, J. VAZQUEZ-CUERVO, E. ARMSTRONG, O. ARINO, C. GENTEMANN, D. MAY, P. LEBORGNE, J. PIOLLÉ, I. BARTON, H. BEGGS, D. J. S. POULTER, C. J. MERCHANT, A. BINGHAM, S. HEINZ, A. HARRIS, G. WICK, B. EMERY, P. MINNETT, R. EVANS, D. LLEWELLYN-JONES, C. MUTLOW, R. W. REYNOLDS, H. KAWAMURA, AND N. RAYNER

An international collaboration of operational and research agencies is producing a new generation of SSTs, combining satellite microwave and infrared data and in situ observations, for NWP, ocean forecasting, ecosystem applications, and climate research.



SSTs off the East Asian coast. See Fig. 4 for more details.

Accurate knowledge of sea surface temperature (SST) distribution and how it changes in time is of growing importance to many agencies worldwide with such diverse tasks as climate variability monitoring, seasonal forecasting, operational weather and ocean forecasting, military and defence operations, validating or forcing ocean and atmospheric models, ecosystem assessment, and tourism and fisheries research. SST is especially important at this time because it is required as an input to the numerical models on which operational ocean forecasting systems are being built. Such systems are being produced in order to serve the needs of industry, commerce, government agencies, and individual seafarers for better knowledge of the ever-changing conditions in the sea.

SST is an ocean variable that is readily measured by satellites and in situ sensors, and it is needed as a key input to forecasting systems to constrain the modeled upper-ocean circulation and thermal structure, and for the exchange of energy ▶

between the ocean and atmosphere. The Global Ocean Data Assimilation Experiment (GODAE) is an international collaboration for ocean forecasting activities, and describes its vision as

> A global system of observations, communications, modelling and assimilation, that will deliver regular, comprehensive information on the state of the oceans in a way that will promote and engender wide utility and availability of this resource for maximum benefit to society. (Smith 2000)

The work of GODAE identified that, if SST observations are to improve model performance, the minimum requirement is that they have an accuracy of better than 0.4 K, be made available in near–real time (within 6 h of observation), and have fine spatial (<10 km) and temporal (6–12 h) resolution. In 2002 GODAE, recognizing that none of the many sources of SST measurements then available could meet this specification, initiated a GODAE High-Resolution SST Pilot Project (GHRSST-PP) to address their needs.

The GHRSST-PP takes existing SST data products as provided by data producers and enhances them by adding additional information and reformatting so that they can be combined to produce the new generation of products using a strategy that is scientifically sound and technically feasible. What was especially interesting for the participants in this project is that success has been achieved not just by solving scientific and technical problems, but also by cooperation at an international level to agree on data product definitions and standards acceptable to both users and producers. Most of all, it has required collaboration between organizations and agencies that produce competing satellite SST data products from different sensor types. Seeking to include all of the major players, GHRSST-PP developed a system that exploits the unique contributions of each sensor type and institutional partner. This article describes the practical steps that the GHRSST-PP has taken so that today it is able to deliver a new generation of SST data products in a form and with a quality that is required by the operational modeling community and broader ocean communities.

MERGING SST DATA FROM DIFFERENT SOURCES. In order to provide frequently sampled SST maps with the dense spatial resolution and global coverage required for input into ocean forecasting models, in situ measurements from buoys, ships of opportunity, and voluntary observing ships are inadequate. Only Earth-observing satellite instruments provide the following necessary sampling capabilities: instruments in geostationary and low-Earth orbits provide high temporal resolution but with only regional coverage, and those in near-polar orbits provide global coverage with repeat times from 12 h to several days. Table 1 shows the different types of sensors and platforms used for measuring SST, and the typical sampling characteristics and absolute accuracy of the SST data produced from each, after applying atmospheric corrections. No single source by itself can meet the GODAE SST specification, but this can be achieved by exploiting the synergy when several sources of SST data are combined and validated against in situ measurements. For example, microwave sensors can measure SST through cloud, although at a poorer spatial resolution than infrared radiometers. Geostationary sensors complement other types with their rapid sampling frequency, giving more opportunity for cloud-free

AFFILIATIONS: Donlon and Rayner—Met Office, Exeter, United Kingdom; Robinson and Poulter—National Oceanography Centre, University of Southampton, Southampton, United Kingdom; Casey—NOAA/National Oceanographic Data Center, Silver Spring, Maryland; Vazquez-Cuervo, Armstrong, and Bingham—NASA PO.DAAC, JPL, Pasadena, California; Arino—European Space Agency, Frascati, Italy; Gentemann—Remote Sensing Systems, Santa Rosa, California; May—NAVOCEANO, Stennis Space Center, Mississippi; LeBorgne—Météo-France/Centre de Météorologie Spatiale, Lannion, France; Piollé—IFREMER/CERSAT, Brest, France; Barton—CSIRO Marine and Atmospheric Research, Hobart, Australia; Beggs—Australian Bureau of Meteorology, Melbourne, Australia; Merchant—University of Edinburgh, Edinburgh, United Kingdom; Heinz—GeoLogics, Hilo, Hawaii; Harris—NOAA/CICS, University of Maryland, College Park, College Park, Maryland; Wick—NOAA/ESRL, Boulder, Colorado; Emery—CCAR, University of Colorado, Boulder, Colorado; Minnett and Evans—RSMAS, University of Miami, Miami, Florida; Llewellyn-Jones—University of Leicester, Leicester, United Kingdom; Mutlow—Rutherford Appleton Laboratory, Chilton, United Kingdom; Reynolds—NOAA/NCDC, Asheville, North Carolina; Kawamura—JAXA/University of Tohoku, Tohoku, Japan
CORRESPONDING AUTHOR: Dr. Craig Donlon, Director of the International GODAE SST Pilot Project Office, Met Office, Fitzroy Road, Exeter EX1 3PB, United Kingdom
E-mail: craig.donlon@metoffice.gov.uk

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-88-8-1197

In final form 14 February 2007

Table 1. Typical sampling capabilities of different types of satellite SST sensors.

Sensor type	Satellite type	Spatial resolution	Resampling interval	Absolute accuracy	Effect of cloud	Depth penetration
Infrared wide swath radiometer	Polar orbit	1–4-km, large off-nadir angles reduce resolution	12 h, global	0.4–0.6 K	Fails over cloud and in the presence of atmospheric aerosol	Skin (~10–20 μm)
Infrared dual-view radiometer	Polar orbit	1–2 km	3 days, global	0.2–0.3 K	Fails over cloud	Skin (~10–20 μm)
Infrared Earth disc radiometer	Geostationary orbit	3–10 km, large off-nadir angles reduce resolution	30 min limited field of view	0.5–0.8	Fails over cloud	Skin (~10–20 μm)
Microwave radiometer	Polar orbit	25–50 km	1–2 days, global	0.5–1 K	Affected by non-precipitating cloud	Subskin (~1–1.5 mm)

views, but only within the field of view limited by the satellite's horizon. Although a dual-view radiometer with its narrow swath has a poor resampling interval, its high absolute accuracy can be used to standardize the bias errors of other sensors.

The distinct characteristics of the SST data products derived from different types of sensors, and even from different ways of processing raw data from the same sensor, mean that a simple blending of SST products is inappropriate. In the operational context assimilating SST data from diverse sources, without careful preprocessing, will clearly result in an inferior performance compared to assimilating carefully processed SST. Traditionally, we know SST as a sea *surface* temperature, but as the "What exactly is the sea surface temperature" sidebar shows, variations in measurement technique introduces uncertainty to this simple definition: the different sampling depths of infrared, microwave, and in situ sensors can result in each sensor recording different temperatures, even when measuring simultaneously, depending on the thermal structure of the upper few meters of water, which in turn depends on the wind, solar insolation, and time of day. Consequently, additional terminology is required to differentiate between measurements of SST. The "What exactly is sea surface temperature" sidebar also explains how sampling the same location at different times of the day can lead to very different temperatures, depending on the conditions affecting diurnal variability of SST. Therefore, GHRSST-PP decided that before data from different sources are used together, the environmental conditions at the time of acquisition need to be known, so that subsequent processing or assimilation can take these factors into account.

Understanding the differing assumptions made in the generation of the various SST source products is also essential. Some satellite products are tuned to in situ subsurface measurements while others represent the skin or the subskin temperature. The GHRSST-PP approach is to make these issues explicit, and to represent them in the assignment of sensor-specific error statistics (SSES), which are explained in the "Uncertainty estimation: Single-sensor error statistics" sidebar. Other factors affecting the errors of particular samples include uncertainty estimates for factors, such as cloud detection for infrared measurements and rain contamination for microwave sensors. These must be provided so that individual error estimates can be deduced for each pixel in every dataset. In recognition of these issues, a key objective of GHRSST-PP is to apply a preprocessing procedure to all of the available level-2 (L2) SST products provided by agencies around the world, which includes the addition of ancillary data to help users interpret SST from different sources.

The GHRSST-PP makes it much easier for users to handle SST data from different sources because of a strict policy of following a standard processing description and providing all data in a common standards-based format. This approach benefits both data users and producers, by simplifying documentation of data, facilitating data exchange, and minimizing the duplication of effort. Thus, as new satellite-derived SST datasets are brought online, only minimal code changes are required by users to accept the data instead of needing a new code for each individual stream. Adherence to internationally agreed upon formats and interfaces gives user agencies the confidence to invest in the development of data access and manipulation tools.

This is important for operational systems [e.g., National Meteorological Services (NMS)], where even small code changes in an operational system are expensive.

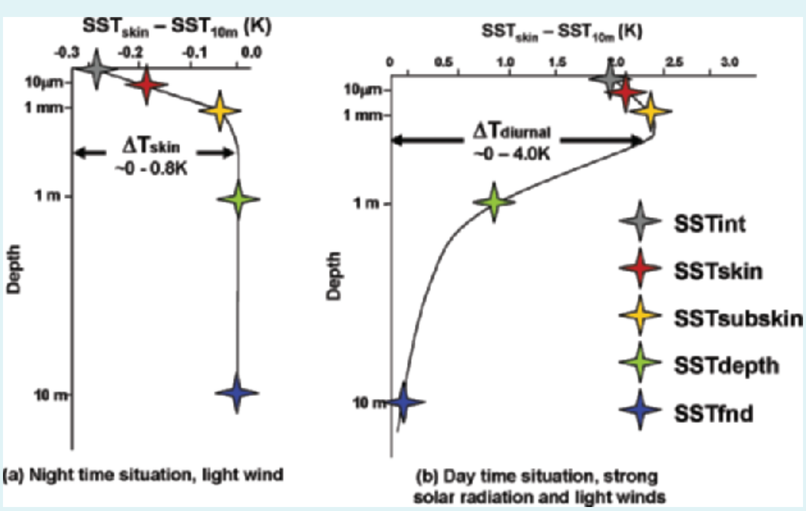
GHRSST-PP PRODUCTS AND SERVICES.

Following these principles, GHRSST-PP provides two types of near-real-time SST products [level-2 preprocessing and level-4 (L4) analysis products] supported

WHAT EXACTLY IS THE SEA SURFACE TEMPERATURE?

SST is a difficult parameter to define exactly because the upper ocean (~10 m) has a complex and variable vertical temperature structure that is related to ocean turbulence and the air–sea fluxes of heat, moisture, and momentum. A theoretical framework is required to understand the information content and relationships between measurements of SST made by different satellite and in situ instruments, especially if these are to be merged together. The definitions of SST developed by the GHRSST-PP SST science team achieve the closest possible coincidence between what is *defined* and what *can be measured operationally*, bearing in mind the current scientific knowledge and understanding of how the near-surface thermal structure of the ocean behaves in nature (Fig. SB1).

The hypothetical vertical profiles of temperature in low wind speed conditions during the night and day shown in the figure encapsulate the effects of the dominant heat transport processes and time scales of variability associated with distinct vertical and volume regimes (horizontal and temporal variability is implicitly assumed). At the exact air–sea interface a hypothetical temperature called the interface temperature (SSTint) is defined, although this is of no practical use because it cannot be measured using current technology. The skin temperature (SSTskin) is defined as the temperature measured by an infrared radiometer typically operating at wavelengths of 3.7–12 μm (chosen for consistency with the majority of infrared satellite measurements), which represent the temperature within the conductive diffusion-dominated sublayer at a depth of ~10–20 μm. SSTskin measurements are subject to a large potential diurnal cycle, including cool-skin-layer effects (especially at night under clear skies and low wind speed conditions) and warm-layer effects in the daytime. The subskin temperature (SSTsubskin) represents the temperature at the base of a conductive laminar sublayer of the ocean surface. For practical purposes, SSTsubskin can be well approximated to the measurement of surface temperature by a microwave radiometer operating in the 6–11-GHz frequency range, but the relationship is neither direct nor invariant to changing physical conditions or to the specific geometry of the microwave measurements. All measurements of water temperature beneath the SSTsubskin are referred to as depth temperatures (SSTdepth), which are measured using a wide variety of platforms and sensors, such as drifting buoys, vertical profiling floats, or deep thermistor chains at depths ranging from 10^{-2} to 10^{3} m. These temperature observations are distinct from those obtained using remote sensing techniques (SSTskin and SSTsubskin) and must be qualified by a measurement depth in meters [e.g., or SST(z), e.g., SST5m]. The foundation SST (SSTfnd) is defined as the temperature of the water column free of diurnal temperature variability (daytime warming or nocturnal cooling) and is considered equivalent to the SSTsubskin in the absence of any diurnal signal. It is named to indicate that it is the foundation temperature from which the growth of the diurnal thermocline develops each day (noting that on some occasions with a deep mixed layer there is no clear SSTfnd profile in the surface layer). Only in situ contact thermometry is able to measure SSTfnd, and analysis procedures must be used to estimate the SSTfnd from radiometric satellite measurements of SSTskin and SSTsubskin. SSTfnd provides a connection with the historical concept of a "bulk" SST considered representative of the oceanic mixed layer temperature and represented by any SSTdepth measurement within the upper ocean over a depth range of 1–20+ m. SSTfnd provides a more precise, well-defined quantity than the previous loosely defined bulk SST and consequently, a better representation of the mixed layer temperature. In general, SSTfnd will be similar to a nighttime minimum or predawn value at depths of ~1–5 m, but some differences could exist. Note that SSTfnd does not imply a constant depth mixed layer, but rather a surface layer of variable depth (depending on the balance between stratification and turbulent energy) that is expected to change slowly over the course of a day.



by user support, data delivery, data management, and quality control services, as illustrated schematically in Fig. 1. Together these make up a consistent system through which any satellite SST measurements can be channeled, conditioned, and evaluated against in situ measurements and other satellite data, which can be easily used by operational forecasting systems, can be used in the construction of real-time SST analyses, and can contribute to the construction of a long-term climate record of global SST distribution.

The GHRSST-L2P product meets the need outlined above for all SST data from various agencies and different sensors to be made available to users in a common format, and with the addition of ancillary information to assist interpretation. For every L2 file (defined as georeferenced SST products) of input data, GHRSST produces a matching L2 preprocessed (L2P) product that contains identical SST values in the same geographical layout (swath latitude–longitude coordinates) as those in the source L2 products. The difference is that each data record (corresponding to a pixel) is augmented with an estimate of the bias error and standard deviation of error derived from the SSES, surface wind speed, aerosol optical depth, surface solar irradiance (SSI), sea ice concentration, time of observation, and a set of quality control flags. The latter fields in the data record are provided as dynamic flags that can be used by different user communities to exclude records that are not suitable for their specific application. For example, wind speed and surface solar irradiance can be used to determine the likelihood of thermal stratification in each pixel, and possibly to estimate the magnitude of diurnal temperature variation (Donlon et al 2002) during the day. Aerosol data, such as model fields derived from the Navy Aerosol Analysis and Prediction System (see information online at www.nrlmry.navy.mil/aerosol/Docs/globaer_model.html), may be used to set a threshold above which SST values from satellite infrared sensors are considered unreliable. The use of these dynamic fields rather than binary mask flags provides more flexibility for users to decide whether a given SST observation is fit for a particular purpose. Figure 2 shows an example of the content of an L2P dataset.

The L2P data format is a network-common data format (netCDF) following the Climate Forecast (version 1.0) convention, thus producing datasets with an extensible common interface format that is Internet "aware" and is appropriate for Open-source Project for Network Data Access Protocol (OPeNDAP) and Live Access Server applications, among others. A unique metadata record is also produced for each L2P product that is used for data discovery and real-time data search and tracking within the GHRSST-PP distributed processing system (see information online at http://ghrsst.jpl.nasa.gov/data_search.html). L2P files are the basic building blocks from which all other GHRSST-PP SST data products are derived.

The GHRSST L4 analysis products provide merged, gridded, and gap-free SST datasets produced by analysis of several complementary inputs. The objective in generating L4 products is to provide the best-available estimate of the SST from a combined analysis of all available L2P (and other) SST data. The L4 products exploit the synergy from using SST derived from in situ, satellite microwave, and satellite infrared sensors, and typically use all available data in a 24-h period prior to

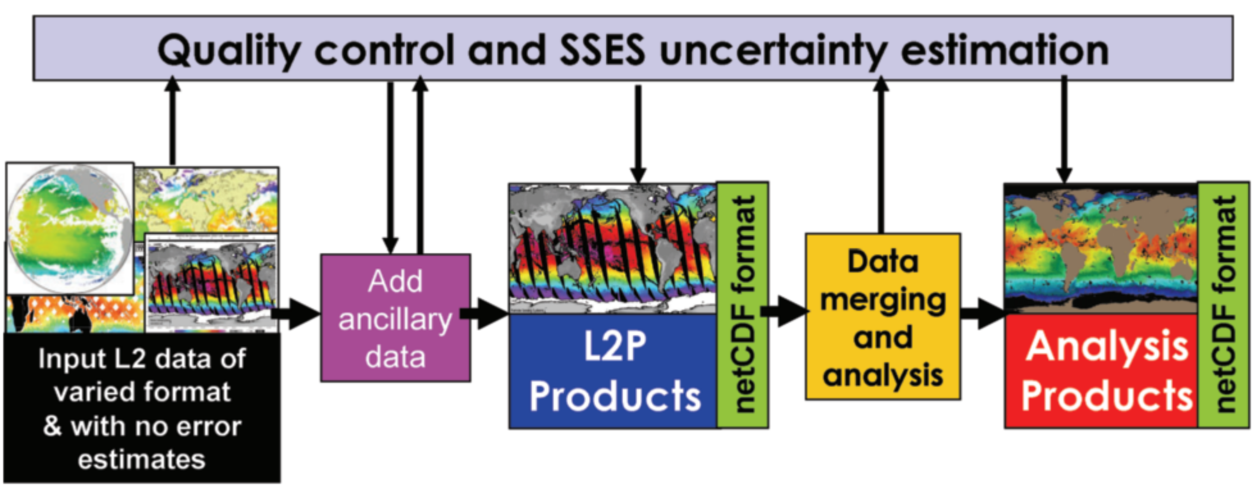
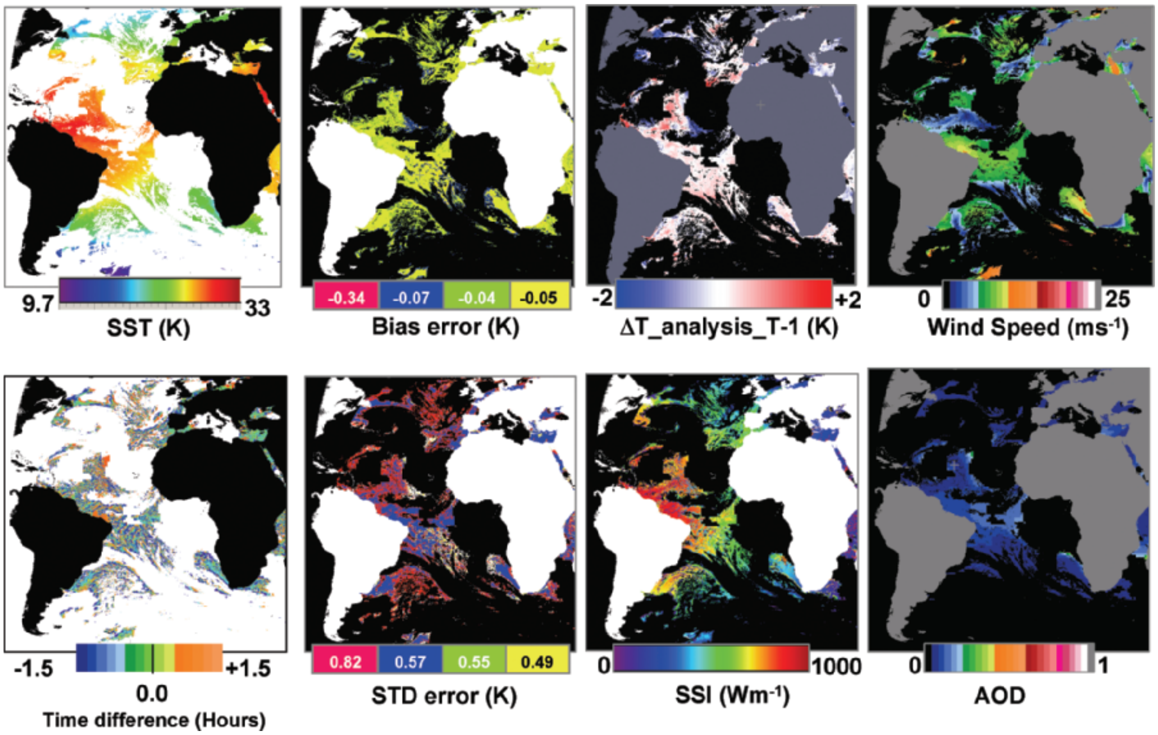


Fig. 1. The data processing strategy of the GHRSST-PP. Satellite and in situ SST data of varied format and with limited error estimates, if any, are first quality controlled and then error estimates are added along with several other auxiliary fields to provide observational data products in a common netCDF (CF-1.0) data format. Data are then merged together to provide complete analysis products.



UNCERTAINTY ESTIMATION: SINGLE-SENSOR ERROR STATISTICS (SSES)

Uncertainty estimates for each SST observation or analysis grid point is one of the key user requirements for GHRSST-PP SST data products. Uncertainty estimates allow users to select the accuracy level suitable for their application and to make optimum use of the SST observations (e.g., in data assimilation). Estimating uncertainties associated with a particular satellite observation is a challenging task, especially considering the vast amount of observations, the highly variable characteristics of the atmosphere (affecting the atmospheric correction algorithms applied to satellite observations), and temporal stability of the satellite instruments themselves. Nevertheless, techniques are emerging that consider statistically the uncertainties associated with each observation in each data stream separately as a SSES. SSESs are based on understanding errors associated with a specific satellite instrument and errors associated with the geophysical retrieval of SST for each individual satellite scene. The simplest L2P SST uncertainty estimation is based on matching satellite SST with in situ observations collocated in space and time to within 25 km and 6 h. A large match-up database of data is required for each satellite instrument, which is then periodically analyzed to derive a mean bias and standard deviation for each satellite system (Fig. SB2).

A more useful spatially and temporally varying uncertainty estimate can be made by analyzing the match-up database as a function of sensor-specific criteria known to cause errors. In one approach, a value (on a scale of 0–5) is defined based on the most likely source of error for a given satellite instrument. In the generic case of infrared satellite SST retrievals, the most likely source of error is cloud contamination (SST measurements using infrared techniques are not possible when cloud is present), amplification of noise at extreme satellite zenith angles, deviation of SST from climatology (and more importantly deviation from atmospheric climatology), and other specific channel differences. In the case of microwave SST retrievals errors can be defined using knowledge of sidelobe contamination in the coastal zone, radio frequency interference, and rainfall flagging (rainfall introduces extra uncertainty in the retrieval of SST), and errors in the estimation of surface emissivity. These criteria are used to classify every pixel within a satellite scene according to the quality scale. Using the match-up database, a bias and standard deviation (SD) uncertainty estimate is derived for each satellite sensor dataset quality value on a regular basis. Based on the relationship between quality value, bias, and standard deviation, SSES uncertainty estimates can then be assigned to all pixels in a given scene. The quality value map generated for the MSG SEVIRI SST dataset of the period from 28 March 2004 to 2 September 2004 is shown in the figure. Clearly seen in this example are excellent quality values in cloud-free regions (yellow areas) and degraded quality values in the proximity of clouds. Shown to the right are the SSES bias and SD estimates for each quality value (1–6 corresponding to cloudy through to excellent in the quality confidence map legend) for the SEVIRI over a 7-month period showing how higher-quality values are associated with lower bias and reduced SD.

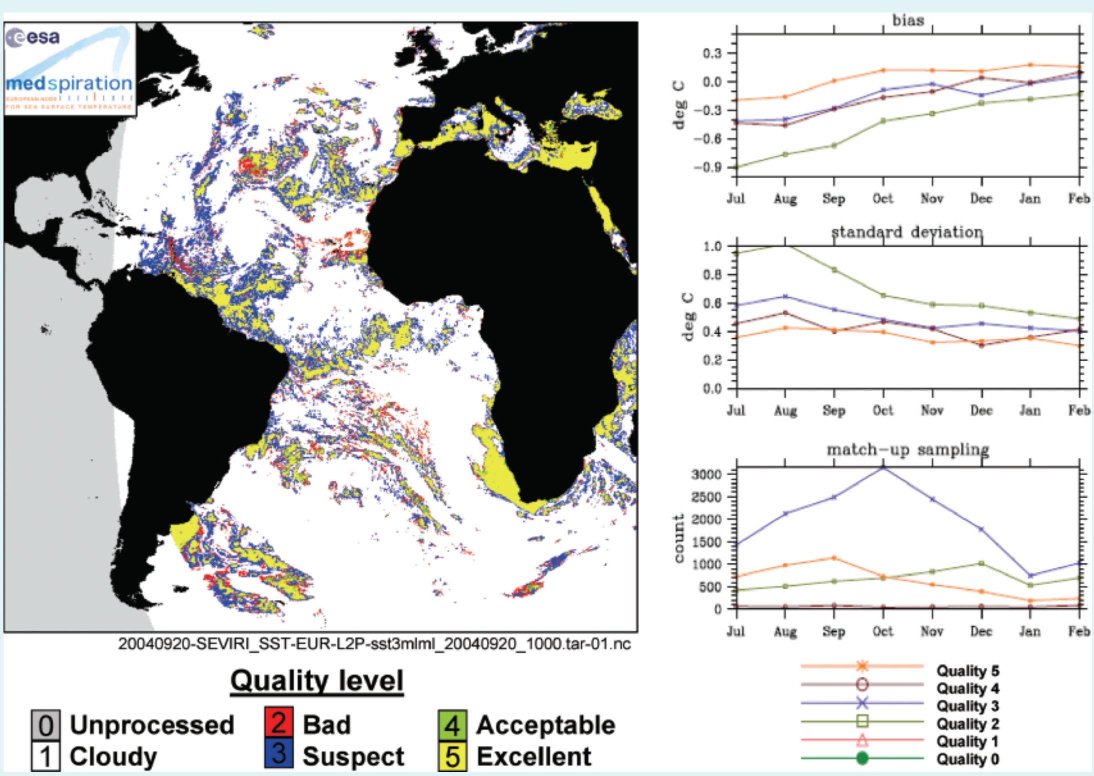
While the SSES process is not able to account for all errors, it provides a method that is functional in a real-time environment, caters to the most obvious satellite-specific errors, and is better than simply taking the latest published figures from sparsely the analysis. As for L2P data streams, the GHRSST-PP L4 data format specification is a netCDF file following the Climate Forecast (version 1.0) convention.

Several L4 production systems with global and regional coverage are currently operational (see Fig. 3) using different analysis methods (e.g., Reynolds and Smith 1994; Guan and Kawamura 2004; Murray et al. 1998; Lorenc 1981). In situ data form an important component of the L4 process because these data can be used to correct for biases between the satellite datasets. New bias adjustment techniques make use of very accurate SST observations obtained form the ENVISAT Advanced Along Track Scanning Radiometer (AATSR) which is capable of SST retrievals accurate to better than 0.3K. Bias correction of all input data used in the analysis procedure is critical to obtaining a valid output (see, e.g., Reynolds et al. 2007). Bias resulting from diurnal stratification and cool-skin effects must also be accounted for using auxiliary data and/or parameterization schemes prior to performing the analysis, which is generally applied to the foundation SST (see "What exactly is sea surface temperature" sidebar).

While SST analysis methods predate the initiation of GHRSST, the availability of L2P data has greatly facilitated their operation and allowed them to

Fig. 2 (facing page). An example GHRSST-PP L2P dataset derived using Meteosat Second-Generation SEVIRI SST processed by the EUMETSAT Ocean and Sea Ice Satellite Applications Facility (OSI-SAF, see www.osisaf.org) data collected over a 3-h period. Shown (from top left to bottom right) are SST, SST bias error, difference from previous reference SST analysis field, surface wind speed (ECMWF), time of observation within a 3-h window (SEVIRI makes observations every 15 min), std dev of SST error, surface solar irradiance (from SEVIRI visible channels), and aerosol optical depth (National Environmental Satellite, Data, and Information System Navy Aerosol Analysis and Ppediction System, NAAPS). The benefit of an integrated data product is clear from this figure, which graphically shows the relationship between variables included within the L2P product.

available in situ validation studies. Furthermore, it is expected that as more experience is gained with the SSES process, better error estimates will be generated based on detailed knowledge of each dataset. For example, a new seven-dimensional lookup table of errors dependent on a combination of satellite instrument and geophysical fields (called a SSES hypercube) offers a promising approach for the MODIS sensor and considerable research for new approaches for microwave SST are in progress.



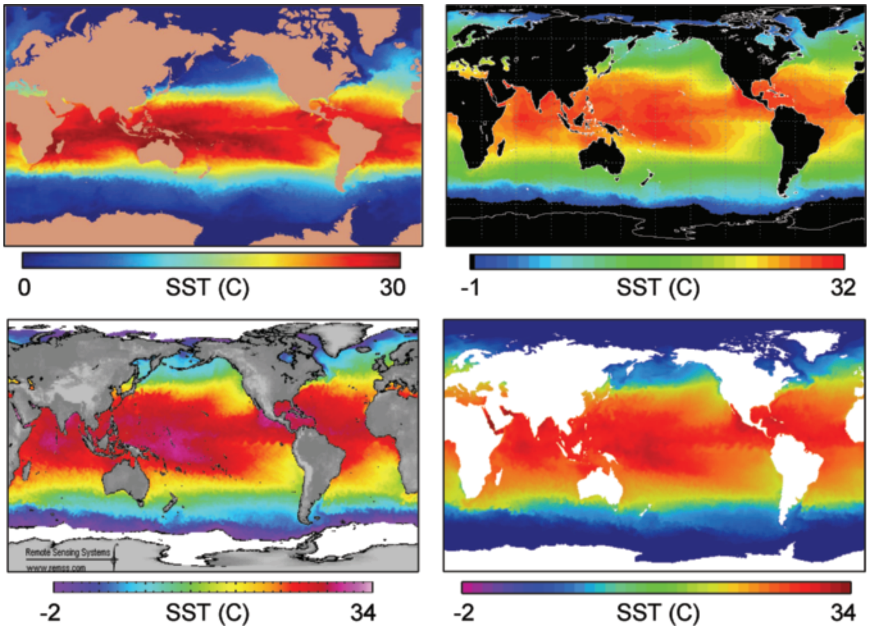


Fig. 3. Several global analysis systems are now operating on a daily basis within the GHRSST-PP framework. (top left) FNMOC 10-km high-resolution SST–sea ice analysis for GHRSST updated every 6 h, (top right) Japan Meteorological Agency 0.25° MGDSST, (bottom left) global 9-km SST analysis system developed by Remote Sensing Systems using TMI, AMSR-E, and *Aqua* MODIS SST data, and (bottom right) a global 1/20° global grid (~6 km) L4 SST analysis produced by the Met Office, called the OSTIA.

exploit more sources of SST than was practicable hitherto. Several dedicated global analysis systems are currently operational, including the following:

- Global coverage, daily updated 6.5-km SST and sea ice data are provided by the Met Office in the United Kingdom using the Operational SST and Sea Ice Analysis (OSTIA; see information at http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html) system. This is a persistence-based multiscale optimal interpolation system (Lorenc 1981) that uses all available GHRSST-PP datasets and in situ observations.
- The U.S. National Ocean Partnership Program (NOPP) Multi-sensor Improved SST (MISST; see www.misst.org) for the GODAE project provides a range of global SST and sea ice analyses updated daily at various resolutions (~9–25 km) generated by the Fleet Numerical Meteorological and Oceanography Centre (FNMOC), Naval Oceanographic Office (NAVOCEANO), National Oceanic and Atmospheric Administration (NOAA), and Remote Sensing Systems (RSS).
- Global 1/4° SST analysis is from the Japanese Meteorological Agency (JMA), using the Merged Satellite and In Situ Data Global Daily Sea Surface Temperature (MGDSST) system. Daily MGDSST maps based on microwave and infrared satellite SST are available online at http://goos.kishou.go.jp/rrtdb-cgi/jma-analysis/jmaanalysis.cgi.
- As part of the BLUElink> Ocean Forecasting Australia project (www.bom.gov.au/oceanography/projects/BLUElink/), the Australian Bureau of Meteorology has modified its existing operational SST analysis system to produce 1/2°-resolution, daily foundation SST analyses over the Australian region (20°N–70°S, 60°E–170°W) based on a univariate statistical (optimal) interpolation system (Beggs et al. 2006; online at http://godae.bom.gov.au).

In addition, a number of ultrahigh resolution (UHR; < 5-km resolution) regional SST analysis products are now being generated, as shown in Fig. 4. UHR products are difficult to generate because the analysis system must capture the local dynamics of the region in a way that preserves the structure and minimizes noise. The following are some examples:

- Since 2000, the New-Generation Sea Surface Temperature (NGSST) Development Group (see information online at www.ocean.caos.tohoku.ac.jp/) has been generating a regional L4 analysis product based on in situ and satellite SST. Satellite observations are objectively merged to generate a daily quality-controlled SST product without gaps resulting from cloud cover, at high spatial resolution (0.05°) over the southwest Pacific area of 13°–63°N, 116°–166°E. Each SST product is generated at around 1600 LST (0700 UTC) at day $T + 1$, using observations acquired on day T.
- The European Space Agency's Medspiration project (information online at www.medspiration.org/) produces a L4 SST product at a resolution of 2 km covering the Mediterranean Sea. This is a particularly challenging area for developing L4 SST products because of strong diurnal variability,

North African atmospheric aerosol, and strong surface ocean dynamics.

A Re-Analysis (RAN) Program is a GHRSST-PP service that is now developing a long-term satellite-derived SST dataset at a high-resolution building on the operational data streams and offline delayed-mode SST datasets not available to the real-time system. Experience with the generation and application of real-time satellite SST datasets indicates a clear need for sustained, long-term reprocessing efforts that optimize product accuracy and temporal stability. By applying extensive quality control procedures, utilizing new technological developments, and conducting routine reprocessing of the entire time series using a consistent set of techniques, the RAN system will facilitate a wide range of additional applications of GHRSST-PP. For example, the reprocessed RAN products will be suitable for use in climate studies as the construction of climate data records (CDRs), an important concept in environmental data stewardship, which dictates long-term accuracy and consistency (e.g., NRC 2000). Also, an accurate and sufficiently long time series of SST is required for initialization of dynamical seasonal forecasts/hindcasts and for their verification using coupled ocean–atmosphere seasonal prediction models. The RAN effort must also verify that biases between the long-term climate record and the modern satellite-derived SST record are properly documented.

The GHRSST-PP RAN program goals are to produce delayed-mode products of higher accuracy and consistency than the real-time SSTs with quantified uncertainties and diurnal variability estimates. The global product is expected to have a spatial resolution of approximately 5–10 km, which will conform to the GHRSST L4 data and metadata format specification, and strive to achieve the ambitious temporal stability requirement of ~0.1 K decade^{-1}. These reanalysis products are expected to extend back to the beginning of the satellite SST period with the start of the five-channel Advanced Very

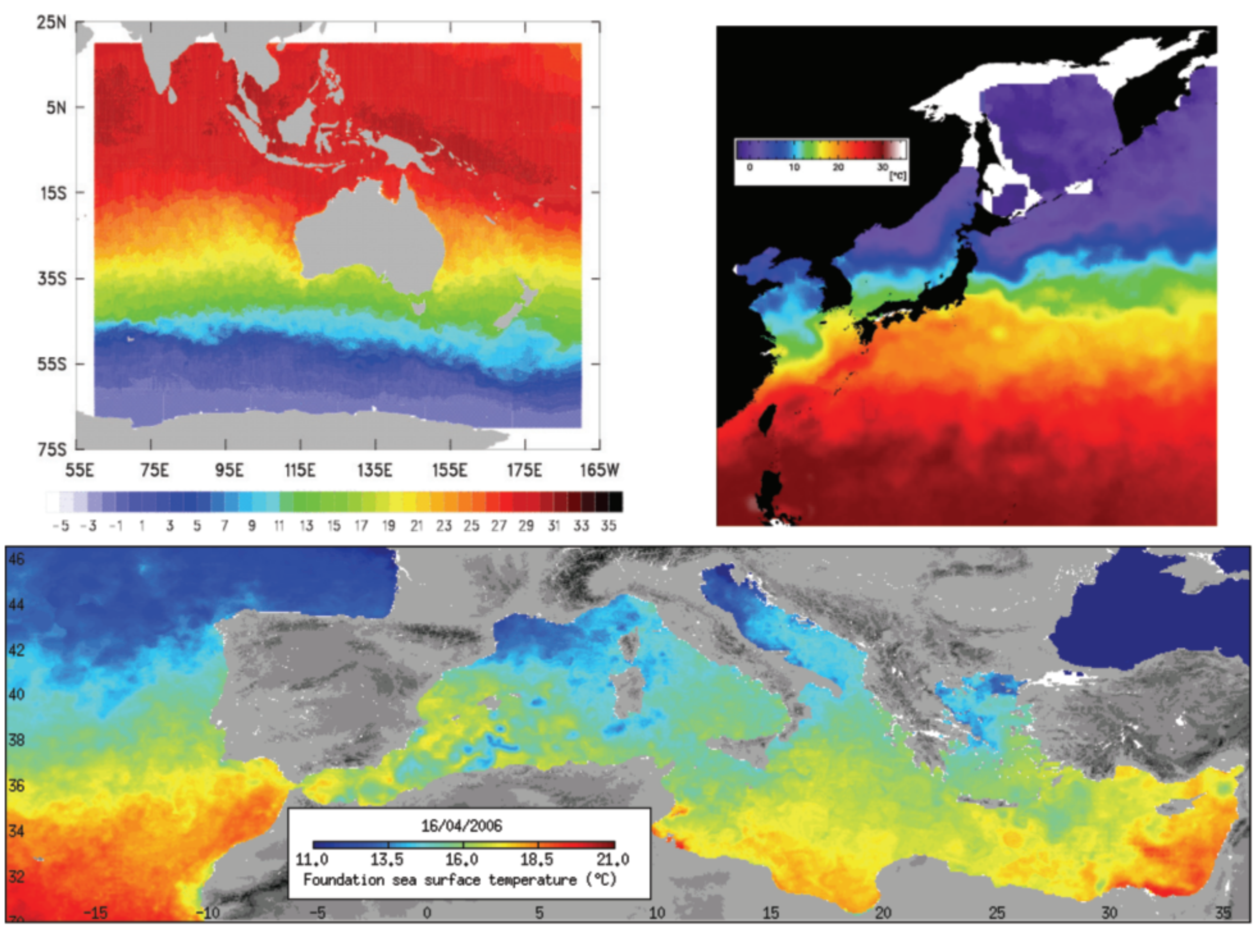


Fig. 4. Example regional coverage SST analysis products. Australian Bureau of Meteorology 1/12° and ultra-high-resolution (<5 km) regional products: Next-Generation SST 1/20° and Medspiration 2-km SST products. The Mediterranean UHR SST shown here is a 2-km analysis (see www.medspiration.org/tools/validation/).

High Resolution Radiometer (AVHRR) series in late 1981. The first formal GHRSST reanalysis products are expected to begin production in late 2007, but L4 intercomparison activities have already begun and will include an initial approach based on ensemble averages, as illustrated in Fig. 5.

The High Resolution Diagnostic Data Set (HR-DDS; see online at www.hrdds.net) is a component service conceived within GHRSST-PP to allow users to interactively view, compare, and analyze SST data products, ocean model datasets, and auxiliary datasets from the various data streams within GHRSST. The HR-DDS system consists of regularly gridded subsets of all available GHRSST SST, resampled if necessary to a common grid, within predefined small sites (typically 2° × 2° in size). There are approximately 200 of these globally distributed sites, chosen not only to provide fairly evenly distributed global coverage, but also to allow detailed examination of the effects of specific atmospheric or oceanic conditions. For example, sites are included to represent regions affected by Saharan dust aerosol, or areas of high spatial and temporal variability, such as the Gulf Loop Current, the Brazil Current, or the Gulf Stream. This service ensures that operational users and scientists have ready access to information in a well-defined format tuned to specific areas and issues that can be used to diagnose faults and data problems immediately.

Every GHRSST file (L2P and L4) is examined by the HR-DDS system, and an HR-DDS file is produced for each site containing an observation of SST. The HR-DDS file contains all ancillary data available at the time of observation, which are resampled onto the

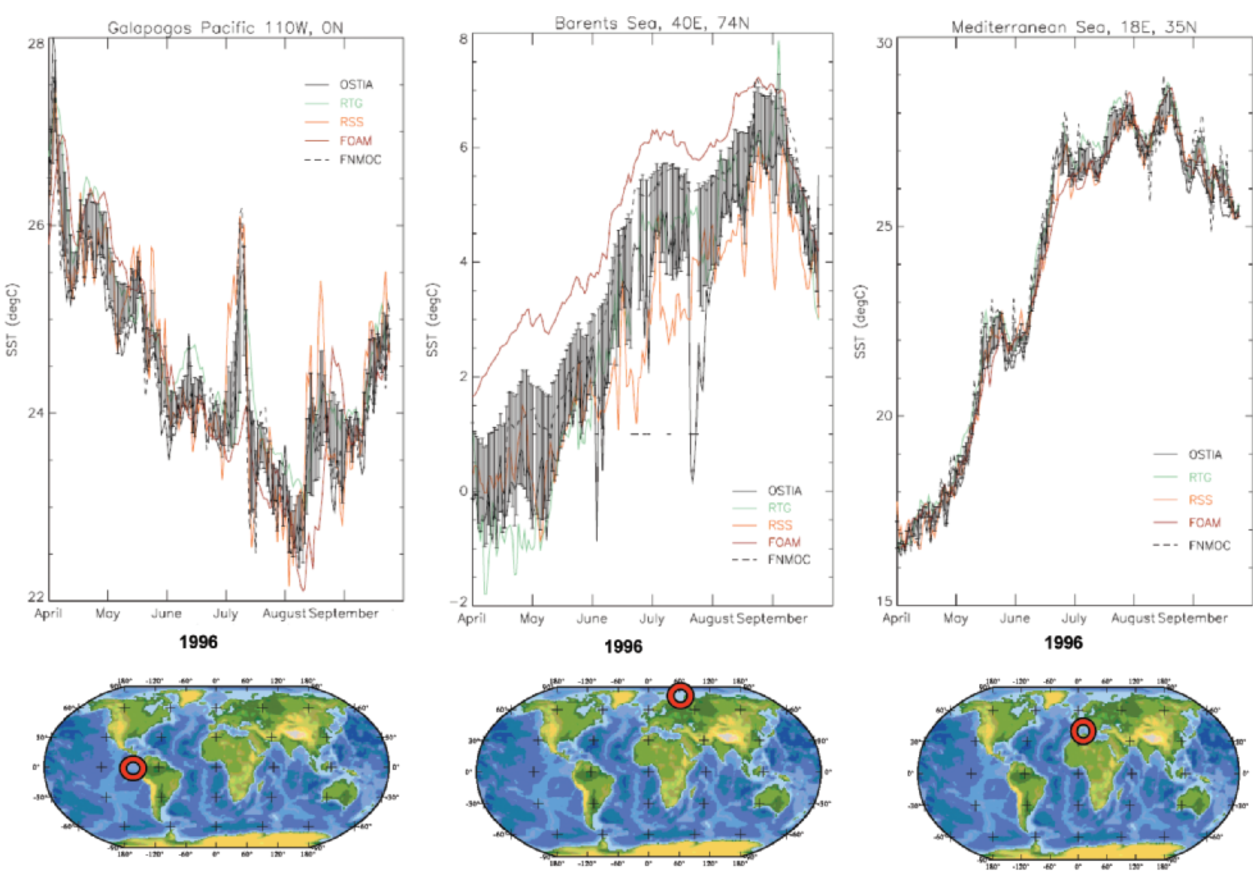


Fig. 5. The GHRSST-PP has implemented an ensemble approach (the GHRSST-PP Multi-Product Ensemble, GMPE) as part of quality control for L4 product development, inter-comparisons, and CDR production. Individual L4 analysis data products are re-gridded using to a common grid specification and inter-compared both spatially and temporally. Shown here are example plots that include five different SST outputs from various analysis systems. All outputs are able to capture tropical instability waves in the Galapagos region and perform well in the Mediterranean. However there are significant differences in the more difficult region of the Barents Sea where analysis outputs show large divergence and bias errors. The GMPE approach helps identify and highlight existing community consensus approaches, strengths, and weaknesses of the various L4 analysis techniques, and areas where more intense research activity is required to create optimal long-term CDRs for SST.

same grid. These files are made immediately available at the HR-DDS Web site via FTP. Additionally, the Web site is linked to an interactive database that records distribution statistics for each field of each HR-DDS file at every site. Work is underway to link the HR-DDS with the GHRSST Match Up Database (MDB) system to create a complete set of Web-based interactive diagnostic tools that better characterize both the magnitude and sources of errors not only in satellite-derived SST fields, but in model and analysis system outputs as well. The interactive Web-based tools provided by the HR-DDS system are used by many different groups to monitor the performance of their L2P or L4 analysis outputs using the "ensemble" of available satellite data and other L4 analyses for a given HR-DDS site. The HR-DDS also provides a resource to investigate problems and errors in L4 analysis outputs. For example, the L4 SST outputs from the Met Office OSTIA are ingested by the HR-DDS system, and Met Office operators make regular use of the HR-DDS system to monitor the consistency of the L4 system output and L2P inputs to the system.

The MDB of collocated satellite and in situ SST is another service of the GHRSST-PP. It is required by GHRSST for the quality control of satellite SST datasets, in particular for deriving or verifying SSES using in situ SST observations from ships, buoys, and profiling floats. Such observations provide a reliable independent reference dataset that must be matched in space and time to satellite observations. Although several independent MDB systems have previously been created by agencies responsible for particular SST products, their formats are diverse, their in situ data sources may be different, and they do not share uniform quality control and spatial/temporal match-up criteria. These important differences make it difficult to compare MDB analyses of different SST products with each other. The GHRSST MDB is intended to remedy this; it is based on a new multisensor SST MDB that is being developed as part of the Medspiration Regional Data Assembly Center (RDAC) project by integrating the in situ data held within a large in situ database and the GHRSST data products. In situ and satellite data are collocated on a daily basis with ±25 km and 6 h of the satellite overpass as a "worst case" scenario, and the match-up criteria can be constrained further in space and time as required. The in situ temperature data sources that are used for the match ups currently include all surface measurements (thermosalinographs on ships and drifting buoy) and data from profiling sensors (Argo floats, XBT/CTD/XCTD from ships, moored buoys). The satellite sources are thus far restricted to products from the European Medspiration project and they will be progressively extended to other GHRSST datasets. Between 100,000 and 150,000 match ups are registered each month within the MDB. All of the ancillary data attached to L2P and L4 products are available for each satellite match up in the MDB.

By adopting a single source of independent quality-controlled in situ data and automating the match-up procedure for all satellite datasets, the GHRSST-PP MDB ensures that all match ups are computed with the same in situ data and with the same level of quality. This removes any ambiguity introduced by different groups producing their own independent uncertainty estimates because uncertainty estimates derived from a single data source can then be reliably compared between satellite sensors. Furthermore, it provides a resource that can be used to investigate the definition of uncertainty estimates to test different approaches and to verify other uncertainty estimation schemes. Access to the GHRSST-PP MDB can be found online at www.medspiration.org/tools/mdb/.

IMPLEMENTATION FRAMEWORK—REGIONAL/GLOBAL TASK SHARING. At the core of GHRSST-PP's success is the international collaboration on which it is based. In the six years of discussion, debate, and planning, the main agencies responsible for operating satellite SST sensors and for producing the primary SST datasets have worked with ocean scientists familiar with the processes affecting the remote sensing of SST, and with key operational users of SST data, to lay down the rule base for the sharing, indexing, processing, quality controlling, archiving, analyzing, and documenting SST data from diverse sources. This is specified in the GHRSST-PP data processing specification document (Donlon et al. 2006), which clearly defines the input and output data specifications, data processing procedures, algorithms, and data product file formats that are common to each GHRSST-PP subsystem. In order for the GHRSST-PP regional/global task sharing (R/GTS) framework to function, all GHRSST products must strictly follow the common data processing specification when generating L2P and L4 data. As a result, users with tools to read data from one RDAC can draw data from any of the others and/or the Global Data Assembly Center (GDAC) and should find it is immediately readable by their systems, which have uniformity within the limits of flexibility permitted by the GHRSST-PP data processing specification.

Moreover, GHRSST-PP was able to move rapidly from defining the processing specification to the present situation in which global L2P and L4 products are being generated in large numbers and beginning to be used operationally, because it established by consensus an implementation framework in which the new data products and services are provided. No attempt was made to impose a top-down structure for commissioning data production. Instead, agreement and commitment to the GHRSST-PP data processing specification facilitated the existing agencies each to contribute a part of the necessary international effort through the regional/global task sharing system that is illustrated in Fig. 6. This is a distributed modular model with a hierarchical distinction between RDAC, GDAC, and the Long-Term Stewardship and Re-analysis Facility (LTSRF).

Each RDAC has responsibility for one or a relatively small number of satellite sensors. For example, the U.S. Naval Oceanographic Office RDAC produces global L2P AVHRR SSTs and a global L4 analysis product that incorporates in situ data. The European RDAC (the Medspiration project, www.medspiration.org) produces real-time L2P SST products from the Environmental Satellite (ENVISAT) Advanced Along Track Scanning Radiometer (AATSR) and Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensors, a regional high-resolution AVHRR product, and an ultrahigh resolution (~2 km) analysis product for the Mediterranean Sea. Another RDAC, generating L2P products from microwave radiometers such as the Tropical Rainfall Mapping Mission (TRMM) Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) is operating at

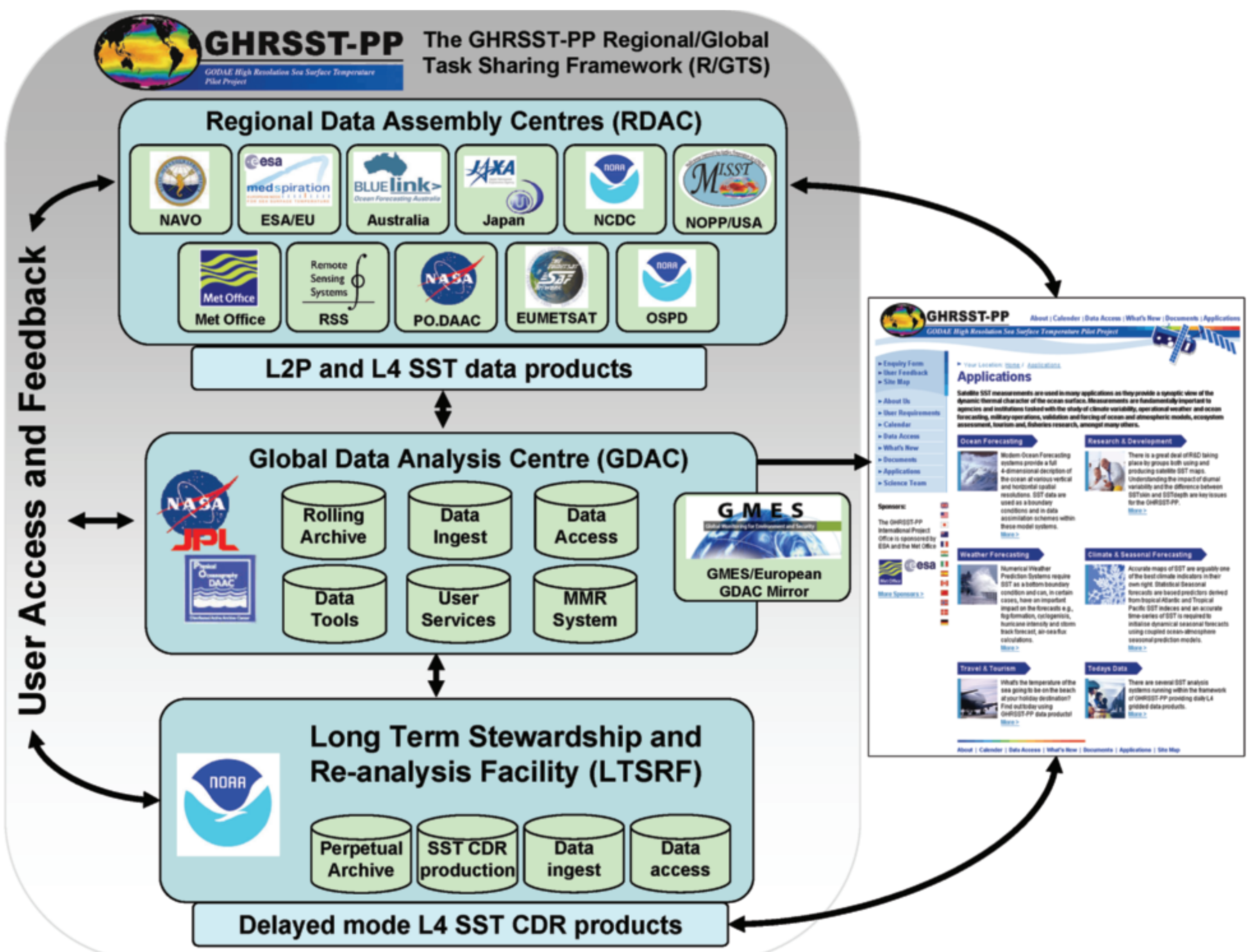


Fig. 6. The GHRSST-PP R/GTS framework. The R/GTS establishes an international set of RDACs, each of which delivers data to a GDAC (online at http://ghrsst.jpl.nasa.gov) and the regional user community. Data are served from the GDAC to near-real-time users and applications for 30 days before the data are sent to the GHRSST LTSRF (at http://ghrsst.nodc.noaa.gov) for long-term archive, stewardship, provision to delayed mode users, and future CDR production. A mirror GDAC will be established in Europe as part of the extensive Global Monitoring for Environment and Security (information at www.gmes.info/) initiative of the European Commission.

Remote Sensing Systems, Inc. The Japan Aerospace Exploration Agency (JAXA) and the JMA operate another RDAC in collaboration with the University of Tohoku (see information online at www.ocean.caos.tohoku.ac.jp/~merge/sstbinary/actvalbm.cgi), providing both regional and global observations and L4 analysis products and L2P products from AMSR-E. The GHRSST-PP also has RDAC services at the Australian Bureau of Meteorology (the BLUElink> project, www.bom.gov.au/oceanography/projects/BLUElink/), providing Australian coverage of L2P and L4 data; at the NOAA Office of Satellite Data Processing and Distribution (OSDPD), providing Geostationary Operational Environment Satellite (GOES)-E and GOES-W L2P data; and at the NOAA/National Climatic Data Center (NCDC), providing L4 analyses. The Physical Oceanography Data Active Archive Center (PO.DAAC) at the NASA Jet Propulsion Laboratory (JPL) in collaboration with NASA's Ocean Biology Processing Group and the University of Miami are also serving as the RDAC for the Moderate-Resolution Imaging Spectroradiometer (MODIS) data. All products are available from the RDAC itself and from the GHRSST-PP GDAC (information at http://ghrsst.jpl.nasa.gov).

Several RDAC systems implement an active user consultation process in order to provide the best possible service to the user community. A GHRSST-PP user support office has been configured at the GDAC facility and provides services to work with the user community and resolve any issues they may raise regarding GHRSST-PP and their specific application. A 6-monthly user consultation workshop is held by the Medspiration project that provides a forum in which user communities can feed back their experience and requirements to the European RDAC teams. Users from operational ocean and NWP systems are represented and the Medspiration service has been modified to suit their requirements several times. Within the MISST RDAC project, a number of key users are engaged at all levels of the project in order to "pull through" the scientific developments within the GHRSST-PP and to demonstrate the benefit of high-resolution SST data products in ocean forecasting and hurricane prediction. User consultation and feedback are essential elements of the GHRSST-PP, and regular interaction with user communities lies at the heart of successfully implementing the GHRSST-PP.

The GDAC, hosted by the NASA JPL PO.DAAC (information at http://ghrsst.jpl.nasa.gov) has a central coordination role for RDAC data streams and users. The GDAC lies at the core of the R/GTS, providing a data management entity and "clearinghouse" for near-real-time data ingestion and distribution, metadata management, and data search/discovery including responsibility for

- the ingestion, quality checking, and management of the near-real-time L2P and L4 products and metadata from RDAC data providers;
- insertion of model-based meteorological and sea ice ancillary fields into GHRSST-PP L2P products, if not already present;
- distribution of all GHRSST products through traditional protocols (i.e., FTP, OPeNDAP) and unique user subscriptions from a 30-day rolling store;
- delivery of 30-day and older GHRSST products and Federal Geographic Data Committee (FGDC)-compliant metadata to the LTSRF for product archiving and reanalysis;
- metadata management and data search services (MMR; see information at http://ghrsst.jpl.nasa.gov/data_search.html) and data tools (e.g., subsetting);
- customer and application support for current and future users; and
- integration of user services at the GDAC with the Application and User Services office of the GHRSST-PP at the international level.

User support is coordinated in collaboration with the GHRSST-PP International Project Office and the JPL PO.DAAC, where customers can submit support requests via a Web site monitored by customer service specialists and data engineers. Applications development is currently focused on integrating GHRSST products into coastal decision support systems and marine resource management [e.g., U.S. Integrated Ocean Observing System (IOOS)]. Measures of effectiveness are tracked and reported at the GDAC to provide overall metrics of the GHRSST-PP program.

At the base of the R/GTS framework is the Long-Term Stewardship and Reanalysis Facility (see http://ghrsst.nodc.noaa.gov) located at the NOAA National Oceanographic Data Center. This delivers individual as well as multisensor-blended GHRSST-PP SST archive products rapidly and routinely. The LTSRF provides both the GHRSST-PP long-term archive and forms the central hub of the distributed GHRSST-PP Re-Analysis (RAN) system. As the name LTSRF implies, complete stewardship, rather than a simple archive in the traditional sense, is required to enable a successful RAN system that protects the significant investment made by RDAC and GDAC teams that have generated GHRSST-PP data products.

The following six broad activities define the overall stewardship responsibilities of the LTSRF:

1) Data ingest, including the receipt, verification, and proper cataloging, via appropriate file- and collection-level metadata, of the input data streams, is defined above as for delayed-mode data.
2) Data are archived, including offsite backup, media migration, and validation of stored data.
3) Data are accessed, including the critical role of providing data and metadata to both a diverse user community and to the LTSRF itself, following relevant standards. All data are provided in a free and open manner via the Internet. Fees for media distribution (CD, DVD, etc.) are limited to cost of production only.
4) Application utilities and support to help data providers/developers use and test GHRSST-PP data in a variety of applications are developed. As data providers/developers become much more knowledgeable about the data they are able to quickly identify weakness and rapidly validate the use of GHRSST-PP data in new application areas and provide feedback on the data quality. The latter is essential for proper long-term stewardship of GHRSST-PP data.
5) The user services component of the LTSRF not only provides the standard user assistance with questions about the data, but also serves as the vital feedback loop to receive user input on problems, new applications, and directions for future improvements. This component will be primarily achieved through user services support of the GDAC at the PO.DAAC.
6) Reanalysis functionality enables reprocessing of the entire GHRSST-PP collection at a sufficiently rapid pace to take advantage of new delayed mode datasets for new analysis techniques.

In practice, 30 days after an observation has been made, GHRSST data are transferred from the GDAC to the LTSRF where stewardship is provided in perpetuity. A large metadata transformation process, which begins at the GDAC to create Federal Geographic Data Committee–compliant records for every daily collection of GHRSST products, is also completed at the LTSRF.

Users may access data at any of the GHRSST-PP centers in real time and in delayed mode, using FTP and OPeNDAP protocols. At all levels of the GHRSST international framework, the user community is fully engaged in the development and specification of services and data products. Through the GHRSST-PP R/GTS, observation, and analysis SST datasets can be obtained through robust operational data servers, in near–real time, in the same generic format and with uncertainty estimates. A large amount of SST data have been made available to the community in this way and the GHRSST-PP may serve as a model for other international projects making a contribution to the Global Earth Observation System of Systems (GEOSS).

APPLICATIONS. The successful application of GHRSST-PP data products and services within operational, scientific, and commercial sectors is at the center of the GHRSST-PP. Sustained operations are required, providing SST observations and analyses with error statistics plus bias and diurnal cycle corrections that are required for assimilation into ocean and atmosphere forecast models at a variety of time and space scales. Operational agencies are now starting to engage with GHRSST-PP as it transits to sustained operations. Primary applications include numerical weather prediction, and ocean, climate, and seasonal forecasting. The GHRSST-PP is working together with several national meteorological services [including the JMA, Met Office, Meteorologisk Institutt (Met.no) of Norway, Bureau of Meteorology (BoM) of Australia, Danish Meteorological Institute (DMI) of Denmark, and the Fleet Numerical Meteorological and Oceanographic Center] to ensure that high-quality, readily accessible SST data products, tailored to their requirements, are delivered on an operational basis. Making satellite SST datasets accessible in this way frees up users' time to concentrate on applying the data rather than gaining access to it in the first place. An important goal of the GHRSST-PP R/GTS is the operational uptake of products, which will happen only if NWP systems are able to demonstrate a useful improvement to their forecast skill. This is one of the ways by which the success of GHRSST-PP should be judged. The following sections briefly review several applications and their use of high-resolution SST data products.

Numerical weather prediction. SST and sea ice are dynamic and have an important interactive role in determining the behavior of the overlying atmosphere, and numerical weather prediction (NWP) model systems need to be properly constrained on a regular basis to ensure an accurate forecast, otherwise significant errors may result (e.g., Thiébaux et al. 2003). SST affects the formation and subsequent evolution of tropical cyclones, convection and thunderstorms, cyclogenesis itself, sea fog, and sea breezes. SST gradients are better represented in high-resolution SST products (Berg et al. 2004) and have been shown to significantly alter the surface wind stress field (Chelton et al. 2001). Within the MISST project, high-resolution GHRSST-PP outputs are now being used to improve hurricane forecasts. Recently, the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP model has been shown to have sensitivity to the spatial resolution of the SST fields used as the bottom boundary condition (Chelton and Wentz 2005). The application of near-all-weather coverage provided by microwave radiometers is extremely useful in hurricane intensity forecasting because traditional infrared SST products in the presence of clouds do not adequately resolve some SST features (e.g., cool-water upwelling from hurricane activity) having a direct impact on storm strength (Wentz et al. 2000). High-resolution SST is also used to help upper-air forecasters at the World Aviation Forecast Centre (WAFC) monitor areas that are more likely to develop cumulonimbus activity, which can produce a significant threat to aircraft. The GHRSST-PP data streams offer significant advances in meeting these requirements and are being used and tested at a number of operational centers requiring daily high-resolution analyses and access to NRT satellite SST observations of both the SST and sea ice (extent and concentration).

Ocean modeling. For those who work at sea or live near the coast, forecasts of ocean conditions can be just as important as forecasts of the weather. The primary requirement is for near-shore forecasts of both physical and biological parameters several times per day. Rough seas and strong currents can make many marine activities difficult or dangerous. High waves or storm surges can lead to coastal flooding. Ocean currents transport and disperse oil slicks and other marine pollution. Changes in ocean temperature can affect the marine ecosystem, from plankton through to fisheries.

Ocean information is required by many different organizations for many purposes [for disaster mitigation (oil and chemical spill drift forecasts), ensuring safety at sea (e.g., diving, search-and-rescue operations), marine and offshore operations (e.g., oil drilling operations, cable laying, and ship routing), operational wave forecasting, sustainable development, and exploitation of the marine environment]. For military operations, operational ocean forecast systems are used to determine ship and submarine acoustic tactics, ship and submarine navigation, in concert with ecosystem models to identify and predict regions of bioluminscent algal blooms, and visibility during diving operations.

Coupled physical and biogeochemical ocean models are expected to mature in the coming years to provide new knowledge and information that will help monitor the exchange of important greenhouse gasses (e.g., carbon dioxide) across the air–sea interface, and to monitor the quality of near-surface waters and plankton distributions for input into the management of fisheries. Most importantly, as NWP systems attain ever higher resolutions, ocean model outputs must be coupled to the atmospheric models in real time.

Operational ocean forecast systems produce forecasts (for several days) of three-dimensional ocean temperatures, salinities, and currents, and sea ice properties on a routine daily basis. High-resolution SST observations and analyses are required for initial and boundary conditions that constrain the models using advanced data assimilation techniques. Accurate and high-resolution climatologies of SST are required because the models are often weakly relaxed toward monthly variations. The enhanced quality and availability of SST inputs from the GHRSST-PP are helping to improve open-ocean nowcasts and forecasts that, in turn, help improve the prediction of coastal, shelf, and regional subsystems by providing better boundary and initial conditions. Several systems within the framework of GODAE, such as the Marine Environment and Security for the European Area (MERSEA) integrated project (Desaubies 2005), are using GHRSST-PP data in data assimilation systems and for validation and verification studies.

Seasonal forecasting. At global scales, SST patterns change relatively slowly and can be reasonably predicted up to 6 months ahead or longer in some regions of the world. The links between regional SST patterns and the atmosphere can be represented in models of the atmosphere and ocean or statistically related to SST observations or data-driven analysis. Many statistical seasonal forecasts are based on predictors derived from tropical Atlantic and tropical Pacific SST indices, and dynamically coupled climate models increasingly form the basis of many seasonal prediction systems. The strongest relationship between SST patterns and seasonal weather trends are found in tropical regions (Johansson et al. 1998). Strong signals are associated with the El Niño phenomenon in the tropical Pacific, roughly every three or four years, which can disrupt the global pattern of normal weather, including large changes in seasonal rainfall patterns (droughts in some regions and floods in others). Links between SST and seasonal weather can be found in other parts of the globe, such as the tripole pattern of SST in the Atlantic, its relationship to the North Atlantic Oscillation, and its impact on European winter forecasts (e.g., Folland et al. 2006).

Seasonal forecasts, given in terms of probability, provide information about likely conditions averaged over the next few months based on long-term averages. The relationship between weather and SST is strongest when long-term weather averages are used and, because the uncertainty in forecasts generally rises as the forecast range increases, probabilistic seasonal forecasts are different in format when compared to more familiar daily forecasts. The enhanced SST data products provided by the GHRSST-PP, as it builds up a global high-resolution SST CDR archive within the Re-Analysis program, will provide a unique source of data for seasonal forecasting activities. In the short term, GHRSST-PP global analysis products can be used to initialize seasonal forecast models and verify seasonal forecasts in hindcast runs.

Climate monitoring. SST maps are arguably one of the best climate indicators with a history of measurement and analysis. The reliable SST data record extends from about 1870, although considerable effort is required to quality control biases in these observations caused by changes in the design of ships, observing practices, and the geographical distribution of shipping routes. A strong motivation for climatology research and development is to reduce uncertainty in climate prediction and to provide input and advice to climate change assessments. In this context, SST is required for climate model initialization, diagnostics, and fundamental climate monitoring using CDR. The most important requirement is that all observations are accurate and free of bias. Considering the best estimates of global warming trends, SST datasets should be exceptionally stable to better than 0.1 K decade^{-1}, and with a mean zero bias.

Satellite data provide a unique and extensive source of global coverage SST observations. But, in order to meld these together with existing SST climatologies based on in situ observations alone, the biases resulting from satellite measurement techniques, instrument drifts, calibration, etc., must be properly applied. Accounting for strong diurnal variability of the SST (e.g., Sathyendranath et al. 1991) is a particular challenge, and for studies of diurnal SST variability, hourly products of SST and SSI at full native resolution are now becoming available from geostationary satellite imagers [Meteosat Second Generation (MSG) SEVIRI, GOES]. Due to the vast amount of data that is provided by satellite instruments compared to in situ observations, even very small errors will have a significant impact. Cross calibration between follow-on instruments must be planned and executed, and adherence to established climate monitoring principles is essential. Achieving a zero bias (and verifying that it is true) is a long and demanding process using in situ observations and analysis. It can only be done through careful reference to a well-documented and calibrated subset of SST measurements derived from the in situ network of quality-controlled buoys or using reference quality satellite observations such as the ENVISAT AATSR. Through community consensus, this is the most truthful measure of SST available today. The GHRSST-PP Re-Analysis program is designed to work with the climate observations and application community to ensure that the best-available SST and sea ice record during the satellite era is developed and maintained in an ongoing manner (including regular reanalysis runs using a variety of different techniques) for the benefit of climate research and prediction.

CHALLENGES. The GHRSST-PP is a large international project that provides a framework for the exchange, processing, and application of satellite SST products. It has over $18 million invested by projects in Europe, the United States, Japan, Australia, Korea, and China which is expected to rise as other international agencies join the project. The GHRSST-PP is making full use of international satellite SST and in situ SST outputs and recognizes the importance of the rapidly growing operational SST user and producer services that are now provided by agencies all over the world. Operational sea ice concentration, surface solar irradiance, aerosol optical depth, and wind speeds are all inputs to the GHRSST-PP and constitute the core datasets for the GHRSST-PP RDAC services. User and producer communities should consider the L2P format and methods as a baseline standard for the present and next generation of satellite SST data products and services, which represent the best international scientific consensus opinion on SST data format and quality control procedures. This would allow users to be fully prepared for the application of these data using a standard set of well-documented input/output utilities that are common to all satellite SST datasets with obvious benefits to the application community. Continued investment to provide the best SSES uncertainty estimates on a satellite-by-satellite basis as well as for in situ observations is required. As the SST satellite network changes in the coming years, work is required to account for diurnal variability through modeling studies, to develop enhanced SST data-blending techniques, provide better estimates of sea ice quantities in the marginal ice zone, conduct comprehensive ongoing validation/verification studies, compensate for the shift in Earth observation time due to orbit drift of satellites, and manage the GHRSST-PP datasets in an internationally distributed context. While considerable progress has already been made, the real challenge is to "pull through" the committed investment, immense knowledge, and experience gained within the GHRSST-PP teams as the project now transitions into sustainable operations. Full details of the GHRSST-PP, its data products, and services are available online at www.ghrsst-pp.org.

ACKNOWLEDGMENTS. The GHRSST-PP International Project Office is supported by the European Space Agency (ESA) and the Met Office, 2003–09. Special thanks to Mike McCulloch at the Met Office for preparing Figure 5.

REFERENCES

Beggs, H., N. Smith, G. Warren, and A. Zhong 2006: A method for blending high-resolution SST over the Australian region. BMRC Research Letters, No. 5, 7–11. [Available online at www.bom.gov.au/bmrc/pubs/researchletter/reslett_05.pdf.]

Berg, R., C. Sisko, and R. DeMaria, 2004: High resolution SST in the Ships model: Improving operational guidance of tropical cyclone intensity forecasts. Preprint, *26th Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Meteor. Soc., CD-ROM, 14A.3.

Chelton, D. B., and F. J. Wentz, 2005: Global microwave satellite observations of sea surface temperature for numerical weather prediction and climate research. *Bull. Amer. Meteor. Soc.,* **86,** 1097–1115.

——, and Coauthors, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical Pacific. *J. Climate,* **14,** 1479–1498.

——, M. G. Schlax, M. H. Freilich, and R. F. Milliff 2004: Satellite measurements reveal persistent small-scale features in ocean winds. *Science,* **303,** 978–983.

Desaubies, Y., 2005: The MERSEA integrated project. *Ocean Weather Forecasting: An Integrated View of Oceanography,* E. Chassignet and J. Verron, Eds., Springer Verlag, 449–453.

Donlon, C. J., P. J. Minnett, C. L. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward, and M. J. Murray, 2002: Toward improved validation of satellite sea surface skin temperature measurements for climate research. *J. Climate,* **15,** 353–369.

——, and the GHRSST-PP Science Team, 2006: The GHRSST-PP data processing specification version 1.6. 241 pp. [Available online at www.ghrsst-pp.org.]

Folland, C. K., D. E. Parker, A. A. Scaife, J. J. Kennedy, A. W. Colman, A. Brookshaw, S. Cusack, and M. R. Huddleston, 2006: The 2005/06 winter in Europe and the United Kingdom: Part 2—Prediction techniques and their assessment against observations. *Weather,* **61,** 326–362.

Guan, L., and H. Kawamura, 2004: Merging satellite infrared and microwave SSTs: Methodology and evaluation of the new SST. *J. Oceanogr.,* **60,** 905–912.

Johansson, Å., A. Barnston, S. Saha, and H. van den Dool, 1998: On the level and origin of seasonal forecast skill in northern Europe. *J. Atmos. Sci.,* **55,** 103–127.

Lorenc, A. C., 1981: A global three-dimensional multivariate statistical interpolation scheme. *Mon. Wea. Rev.,* **109,** 701–721.

Murray, M. J., M. R. Allen, C. T. Mutlow, A. M. Zavody, M. S. Jones, and T. N. Forrester, 1998: Actual and potential information in dual-view radiometric observations of sea surface temperature from ATSR. *J. Geophys. Res.,* **103,** 8153–8165.

Reynolds, R. W., and T. M. Smith, 1994: Improved global sea surface temperature analyses. *J. Climate,* **7,** 929–948.

Sathyendranath, S., A. D. Gouveia, A. R. Shetye, P. Ravin-dran, and T. Platt, 1991: Biological control of surface temperature in the Arabian Sea. *Nature,* **349,** 54–56.

Smith, N., 2000: The GODAE strategic plan. GODAE Rep. 6, 36 pp. [Available online at www.bom.gov.au/bmrc/ocean/GODAE/Planning/Strategic_Plan.pdf.]

Thiébaux, J., E. Rogers, W. Wang, and B. A. Katz, 2003: New high-resolution blended real-time global sea surface temperature analysis. *Bull. Amer. Meteor. Soc.,* **84,** 645–656.

Wentz, F., C. Gentemann, D. Smith, and D. Chelton, 2000: Satellite measurements of sea surface temperature through clouds. *Science,* **288,** 847–850.